A Method to Stabilize a Power Hardware-in-the-loop Simulation of Inductor Coupled Systems

Miao Hong, Satoshi Horie, Yushi Miura, Toshifumi Ise, Christian Dufour

Abstract--**This paper proposes a method to stabilize a power hardware-in-the-loop (PHIL) simulation of inductor coupled systems, in which real time simulator causes instability due to the introduced time delay of the system. The configuration of the PHIL simulation is described and the focused issue is the instability problem of the PHIL simulation. The causes for the instability are analyzed and a solution to stabilize the simulation is proposed and verified by off-line simulation of the investigated system.**

***Keywords*: power hardware-in-the-loop simulation, gas engine cogeneration system, matrix converter.**

I. Introduction

HARDWARE-in-the-loop (HIL) simulation, in which a piece of hardware is incorporated into a simulation system, is widely used in power system. This type simulation provides advantages including testing the hardware on the damaged and faulted conditions, which may not be permitted in actual system. Most HIL simulation carried out previously was used to test controllers in the power system, which was so called controller hardware-in-the-loop (CHIL) simulation. In CHIL simulation, signals exchanged between the simulated part and the real part of the system are low power and voltage level (+/- 15V, mA) and can be implemented by A/D and D/A converter conveniently.

Presently, the HIL concept has been extended to test power components other than controllers, such as generators, motors, power converters, etc. In this case, a real power is virtually exchanged between the simulated part and real part and this is so called power hardware-in-the-loop simulation (PHIL). Comparing to CHIL simulation, there are relatively less reports about PHIL simulation. One of the key issues which limit the development of the PHIL simulation is the instability problem. In PHIL simulation, a power interface is introduced to interface a simulation model and the hardware under test. As a result, the unavoidable problems, such as time delay, limited frequency band, noise injection, etc, may cause the PHIL simulation instability even the original real system is stable.

There are some papers [1]-[3] about PHIL simulation. In [1], a PHIL simulation with a nonlinear load was successfully achieved. Nevertheless, there was no mention about the instability problem. Papers [2] and [3] both presented that the occurrence of the instability was caused by the sampling frequency of the power interface. In [4], different interface methods were presented and compared. The conclusions of [4] showed that different interface algorithm provided different stable ability. However, which factors were the main reasons for the instability and how to solve the instability problem were not mentioned. Furthermore, the PHIL experiments presented in the above papers used simple model, in which the simulation part was represented by a resistor and the real hardware consisted of a resistor and an inductor. Therefore, these models are relatively simple and the results are not suitable for the other PHIL simulation such as presented in this research.

This paper presents a PHIL for a gas engine cogeneration system with a matrix converter (MC) that is the hardware under test (HUT) in this PHIL. The generator of the system is a synchronous machine and it has a relatively large internal inductance. On the other hand, the MC has a filter between the generator and MC, composed of inductance and capacitance. Therefore, this PHIL is an inductor coupled system.

The inductor coupled system is one of the common circuit configurations for the interconnection of a synchronous machine and a current-source type power converter. For voltage-source type power converters, moreover, the system would also be an inductor coupled one in the case that the transformer that has a leakage inductance is installed between the generator and power converter to match their voltages. In this paper, the focus is the instability issue of the PHIL simulation of the inductor coupled system. The causes for the instability are analyzed and a solution to the instability is suggested and verified.

Section II of this paper includes the construct of the PHIL simulation and the analysis of the instability of the PHIL simulation. The proposed method to resolve the instability problem is presented in section III, together with the verification of the method. The conclusions of this research

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are summarized in the final section.

II. Configuration of the Power Hardware-in-the-loop Simulation of a Gas Engine Cogeneration System

The investigated household type gas engine cogeneration system (GECS) is shown in Fig. 1. In order to improve the electric efficiency of the system, a matrix converter is proposed to substitute a conventional ac/dc/ac converter as shown in Fig. 2 [5].

To investigate interaction of the MC and gas engine/generator, a PHIL simulation system was constructed using the real MC and RT simulator simulated gas engine/generator.

A. Configuration of the power hardware-in-the-loop simulation

The configuration of the PHIL simulation is shown in Fig. 3. In this PHIL, the numerical models of gas engine and the permanent magnet synchronous generator (PMSG) were simulated based on MATLAB/Simulink, compiled by the host computer and then downloaded to the Opal-RT simulator. The output voltage signals of the PMSG were transferred to a power amplifier through the D/A converter which was installed on the simulator. The power amplifier, working as a voltage amplifier, received the voltage signals and regenerated them as physical voltage which was used to drive the proposed MC. The MC, including its controller, was the HUT in this PHIL. On the other hand, the input current of the MC was measured and fed back to the Opal-RT simulator via the A/D converter.

It should be noted that there was a gain in the feedback current circuit. The gain was adopted intentionally for the analysis of the PHIL stability. Obviously, the PHIL was a closed loop system and a fully PHIL was realized only when the gain equaled to 1. The parameters of GE, PMSG, Opal-RT simulator and the power amplifier are summarized in Tables I, II, III and IV, respectively.

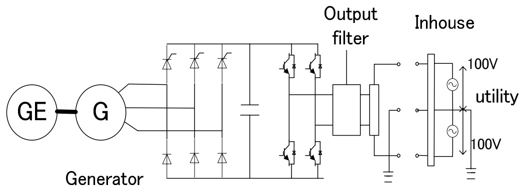

Fig. 1. Configuration of a commercial 1 kW household GECS.

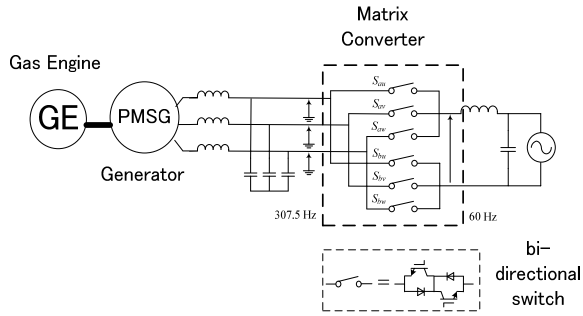

Fig. 2. Configuration of the proposed GECS with a matrix converter.

B. Equivalent circuit of the PHIL simulation

During the implementation of this PHIL simulation, the system became instable when the feedback current gain was larger than 0.65, which is not enough to simulate the real MC and GE/PMSG system.

To analyze this problem, an equivalent circuit of the PHIL was used, which was shown in Fig. 4 and the block diagram of the system can be represented in Fig. 5. Z_1 is the simulated impedances and Z_2 is the real impedance.

From Fig. 5, the open loop transfer function of the PHIL simulation can be presented by (1):

$$G_o(s) = \frac{Z_1(s)}{Z_2(s)} e^{-T_d s} \tag{1}$$

where $T_d = T_{d1} + T_{d2}$. If $T_d = 0$, and then:

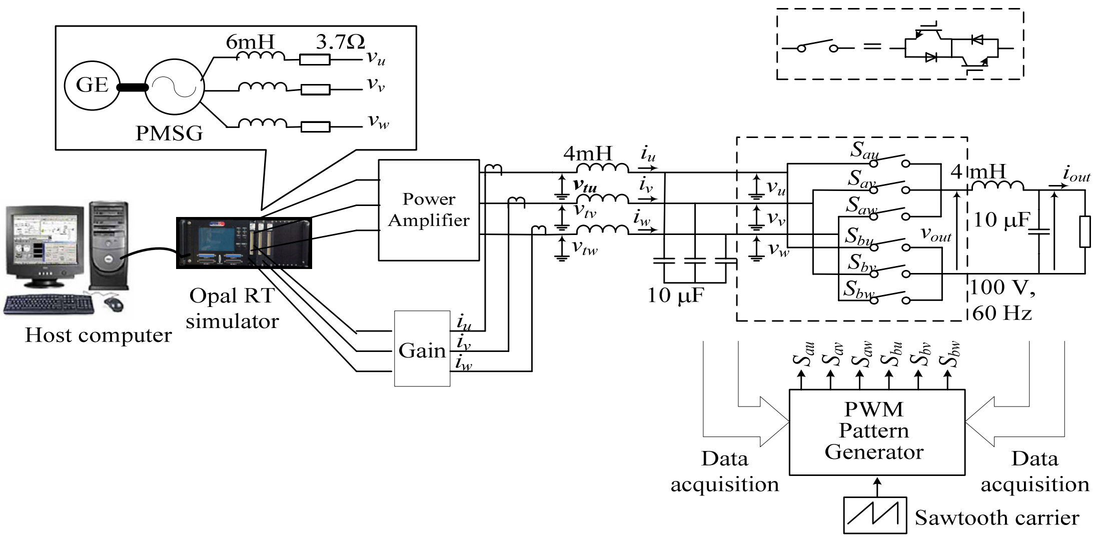

Fig. 3. Configuration of the PHIL-simulation.

TABLE I
PARAMETERS OF GAS ENGINE

Form	Four stroke cycle, one cylinder
Displacement	163 cm^3
Compression ratio	11
Rated speed	2050 rpm
Spark angle	BTDC 22°
Fuel	City gas 13A

TABLE II
PARAMETERS OF PERMANENT MAGNET SYNCHRONOUS GENERATOR

Pole pairs	9
Rated power	1.3 kW
Output phase voltage (generator mode)	189 - 231 V
Output frequency	307.5 Hz
Inductance	6 mH
Resistor	3.7 Ω
Inertia	0.0195 kg·m^2
Flux induced by magnet	0.13 Wb

TABLE III
COMPONENTS OF OPAL-RT SIMULATOR

CPU	3, Intel Core 2 Quad, 2.66GHz
FPGA	1, VirtexIIpro
Op5330 D/A	16 channels, 16bits, 1μs
Op5340 A/D	16 channels, 16bits ,2μs
Digital out	32 channels, 100ns
Digital in	32 channels, 100ns

TABLE IV
RATED VALUE OF POWER AMPLIFIER

Rated power	6 kVA
Rated output voltage	100Vrms, 200Vrms
Output voltage range	0-144Vrms, 0-288Vrms
Maximum output current	20Arms, 10Arms
Output frequency	5Hz-1100Hz

$$G_o(s) = \frac{Z_1(s)}{Z_2(s)} \tag{2}$$

T_d is the whole time delay introduced in the PHIL simulation, which is mainly caused by the computational time of the numerical model and A/D, D/A converters, etc. T_{d1} and T_{d2} represent the delay time in the forward and feedback circuits, respectively. The open loop transfer function of the virtual system which has no time delay is presented by (2). In this PHIL simulation, T_d was 15 μs. Since the factor of $e^{-T_d s}$, which is a pure time delay element, causes linear phase lag in the bode diagram. Therefore, comparing (1) with (2), it can be deduced that even the virtual system in (2) were stable, the PHIL simulation may lose stability due to the factor of $e^{-T_d s}$.

C. Analysis of the instability problem

To analyze the causes of the instability problem, characteristic equation of the system in Fig. 6 can be described in (3).

$$1 + \frac{z_1}{z_2} e^{-sT_d} = 0 \tag{3}$$

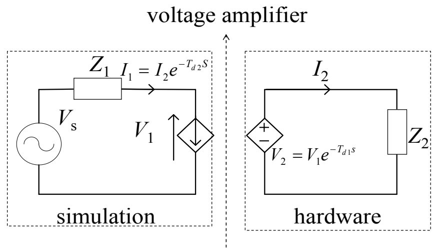

Fig. 4. Equivalent circuit of the PHIL simulation.

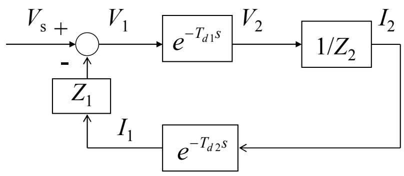

Fig. 5. Block diagram of the equivalent circuit.

To simplify the analysis, e^{-sT_d} was replaced by one order Pade approximation:

$$e^{-sT_d} = \frac{-s+a}{s+a}, a > 0 \tag{4}$$

where a is a constant corresponding to the time delay T_d. It should be noted that a large T_d corresponds to a small a. Assuming that the simulated impedance Z_1 and real impedance Z_2 as follows:

$$Z_1 = R_1 + j\omega L_1 \tag{5}$$

$$Z_2 = R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \tag{6}$$

where R_1, R_2, L_1, L_2 and C_2 represented simulated resistor, real resistor, simulated inductor, real inductors and real capacitor, respectively. This PHIL had no simulated capacitor. Since both the simulated system and real system had inductors, the PHIL simulation was an inductor coupled system. To simplify the system, supposing capacitor C_2 is infinite and substituting (5), (6) and (4) into (3), the characteristic equation can be written as:

$$(L_2 - L_1)s^2 + (R_2 - R_1 + aL_1 + aL_2)s + a(R_1 + R_2) = 0 \tag{7}$$

From (7), to keep the system stable, two conditions calculated from Routh rules and presented as following (8) and (9) must be satisfied.

$$L_1 < L_2 \tag{8}$$

$$a > \frac{R_1 - R_2}{(L_1 + L_2)} \tag{9}$$

Under the condition that C_2 is not infinite, the characteristic equation is:

$$(L_2 - L_1)C_2 s^3 + (R_2 - R_1 + aL_1 + aL_2)C_2 s^2 + (1 + a(R_1 + R_2)C_2)s + a = 0 \quad (10)$$

Equations (11), (12) and (13), which are calculated from Routh rule, must be satisfied to keep the system stable.

$$L_1 < L_2 \quad (11)$$

$$a > \frac{R_1 - R_2}{(L_1 + L_2)} \quad (12)$$

$$a^2(R_1 + R_2)(L_1 + L_2)C_2 + a(2L_1 + R_2^2 C_2 - R_1^2 C_2) + (R_2 - R_1) > 0 \quad (13)$$

From (8), (9), (11), (12) and (13), the following states can be concluded:

(i) For the coupled inductor PHIL simulation, the real inductor must be larger than the simulated inductor to keep the PHIL stable.

(ii) The constant a, which is determined by the time delay T_d, also has effect on the simulation stability. According to (4), smaller time delay means larger value of a. Additionally, from (12) and (13), it can be concluded that a large a benefits to the PHIL stability; on the contrary, a larger time delay will impose more critical requirements on the impedance. Detail relationships between the time delay and the value of impedance which can maintain PHIL simulation stability are presented (9), (10), (12) and (13).

(iii) In the PHIL simulation of Fig. 3, the time delay is as shorter as 15 μs, which means that the constant a is as high as about 1.33×10^5. Consequently, equations (12) and (13) are both satisfied. However, the system is unstable because that the simulated inductance is 6 mH and the real inductance of the LC filter is 4 mH, which was not able to satisfy $L_1 < L_2$.

These conclusions suggest that the instability could often occur in the PHIL of the inductor coupled system, especially including simulated synchronous machines because they generally have large internal inductances.

D. Stable area of the PHIL simulation

To investigate the stable area of the PHIL simulation, an experiment shown in Fig. 6 was carried out. In this experiment, simulation part included GE and PMSG, and the real part only consisted of the LC filter of the MC. The values of the impedance R, L, C are summarized in Table V. The time delay was still 15 μs and the constant a is about 1.33×10^5. Substituting the values of R, L and C into (12) and (13), it can be calculated that the system will lose stability only in the case that the time delay is greater than 0.08 s. This means that this PHIL satisfies the stable conditions (12) and (13). Therefore, the PHIL simulation stability is mainly determined by condition (11), which means that the stability is determined the value of the simulated inductor L_1 and real inductor L_2. The characteristic equations including the feed back gain are:

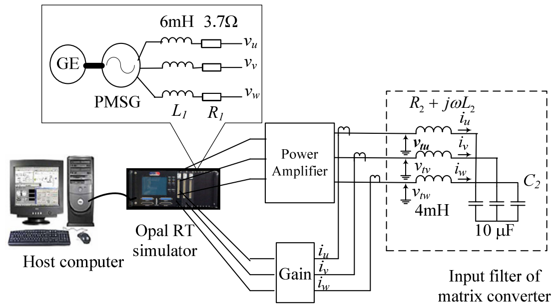

Fig. 6. Configuration of the stability experiment.

TABLE V
VALUES OF THE IMPEDANCE

R_1	3.7 Ω
L_1	6 mH
R_2 (internal resistance of L_2)	1.2 Ω
L_2	4 mH
C_2	10 μF

$$1 + k\frac{z_1}{z_2}e^{-sT_d} = 0 \quad (14)$$

$$(L_2 - kL_1)C_2 s^3 + (R_2 - kR_1 + akL_1 + aL_2)C_2 s^2 + (1 + a(kR_1 + R_2)C_2)s + a = 0 \quad (15)$$

If only the factor of inductor was considered and it could be deduced that the PHIL simulation can maintain stability under the following condition:

$$L_2 > kL_1 \quad (16)$$

Equation (16) also means that the maximum feedback gain k_{smax} in the current control loop that can maintain the stability of the PHIL in Fig. 6 is determined by the following equation:

$$k_{s\max} = L_2 / L_1 \quad (17)$$

To verify (16) and (17), variable parameters were used in the experiment shown in Fig. 6. These parameters are summarized in Table VI. Results of the experiment are shown in Figs. 7 and 8.

TABLE VI
PARAMETERS USED IN THE STABILITY EXPERIMENT

experiment	1st	2nd	3rd
R_1	3.7 Ω	3.7 Ω	3.7 Ω
L_1	3,4,5,6,7 mH	3,4,5,6,7,8 mH	3,4,5,6,7,8,9mH
R_2	1.2 Ω	1.8 Ω	2.4 Ω
L_2	4 mH	6 mH	8 mH
C_2	10 μF	10 μF	10 μF

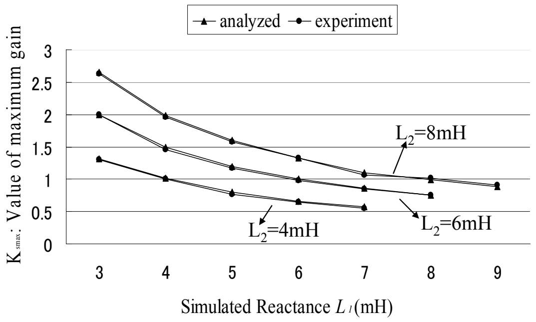

Fig. 7. Comparison of the values: the maximum gain calculated from (17) and the maximum gain obtained by experiment.

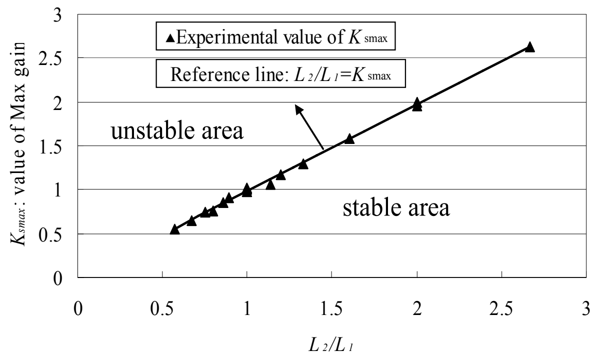

Fig. 8. Relationship of L_2 / L_1 and the gain k_{smax}.

From Figs.7 and 8, the two main following states can be derived:

(i) For a constant simulated inductor, a larger real inductor means a larger stable area for the PHIL simulation.

(ii) The maximum feedback gain k_{smax} in the current control loop, which can maintain the PHIL stability, approximates to the ratio of L_2 / L_1.

III. Proposed Solution to the PHIL Instability

A. Proposed solution to the PHIL instability

According to the previous analysis, the PHIL simulation in Fig. 3 cannot achieve stable since the simulated inductor, which is the inductor of PMSG, is larger than the real inductor, which is the inductor of the LC filter of the test MC.

To solve this problem, we proposed that the simulated inductor was changed from 6 mH to 4 mH, and the inductor of the input MC filter was changed from 4 mH to 6 mH. The modified PHIL simulation is shown in Fig. 9. The total inductor between the voltage source and MC was still 10 mH while the ratio of L_2 / L_1 increased to 1.5. With this modification, stable conditions which were described in (11), (12) and (13) are all satisfied and the stable operation of PHIL in Fig. 9 can be expected.

B. Analysis of the proposed solution

To verify the feasibility of the modification, it should be noticed that this PHIL simulation is used to test the MC. Therefore, this modification should have no effect on the operation of it.

According to the Thevenin's theory, simulated GE and PMSG, power amplifier and LC filter, including the current feedback loop, can be considered as a simulated power source shown in Fig. 9 and equivalent impedance. Fig. 10 is the equivalent circuit of the PHIL simulation system.

The equivalent voltage source V_{es} and the equivalent internal impedance Z_{es} are expressed by the following equations:

$$V_{es} = V_s e^{-T_{d1}S} \tag{18}$$

$$Z_{es} = Z_2 + Z_1 e^{-T_d S} \tag{19}$$

where V_s is the internal voltage of the generator; Z_1 is the

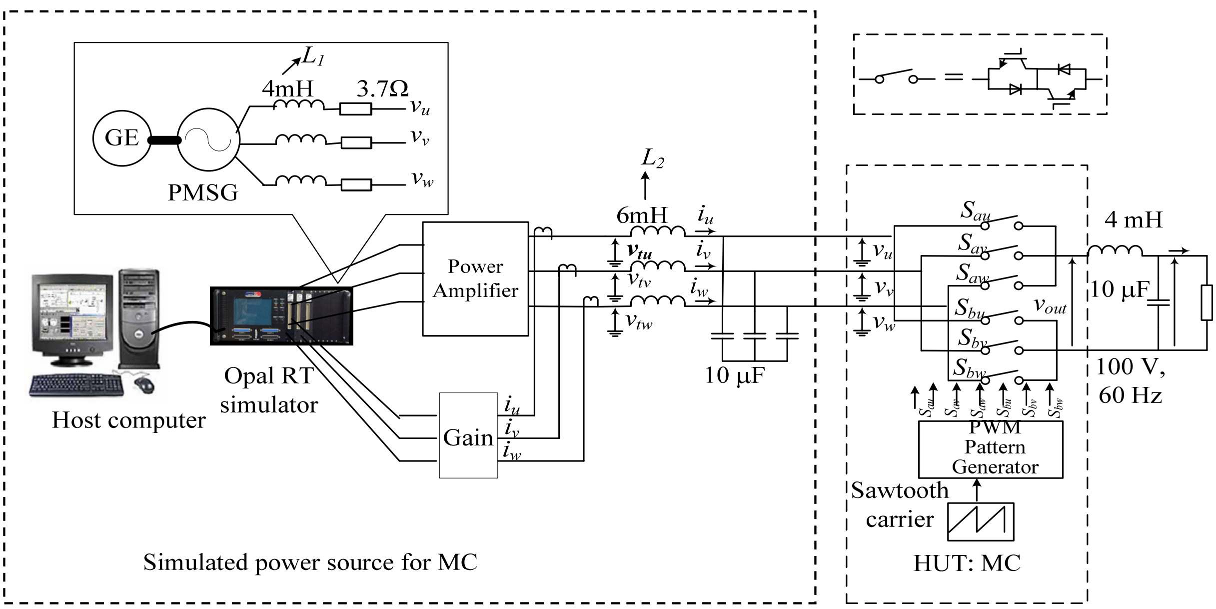

Fig.9. Modified configuration of the PHIL simulation.

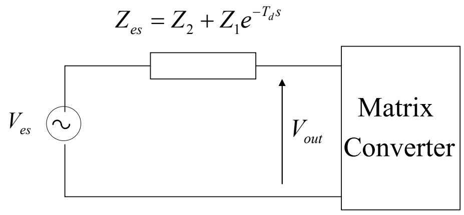

Fig. 10. Equivalent circuit of PHIL simulation.

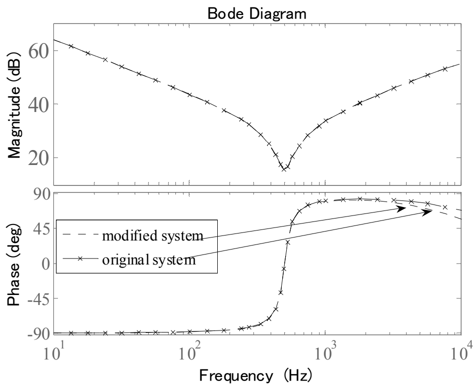

Fig. 11. Bode diagram of the equivalent internal impedance of the original PHIL simulation and modified PHIL simulation.

simulated impedance that is the generator impedance, $R_1+j\omega L_1$; Z_2 is the impedance of the MC input filter, $R_2+j\omega L_2+1/j\omega C_2$; T_{d1} is the delay time in the PHIL simulation forward circuit; T_d is the total delay time in the system. Equation (18) shows that the modification has no effect on the equivalent voltage source V_{es}.

Fig. 11 is the bode diagram of the original and modified equivalent internal impedances Z_{es}. This figure shows that characteristics of two equivalent impedances are almost the same in the bandwidth region from 0 Hz to 1000 Hz. As mentioned previously, the bandwidth of the power amplifier in this PHIL simulation is 0 Hz to 1000 Hz, and therefore, this modification of values of two inductors should have no influence on the operation of the test MC.

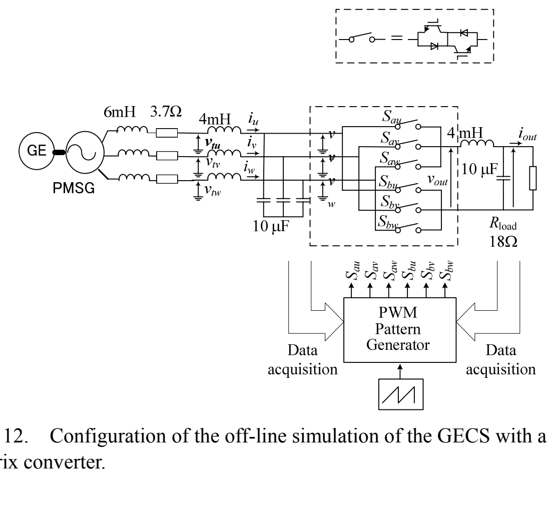

Fig. 12. Configuration of the off-line simulation of the GECS with a matrix converter.

C. *Results of the modification PHIL simulation and verification of the proposed solution*

Stable operation of the modified PHIL simulation shown in Fig. 9 was achieved. In order to verify the results of the PHIL simulation, off-line simulation of the original system shown in Fig. 12 was also carried out based on MATLAB/ Simulink and SimPowerSystems. It should be noted that the inductor of the generator was still 6 mH while the inductor of the input filter of the MC was still 4 mH in the off-line simulation. The parameters used in the off-line simulation are summarized in Table VII. Both the results of PHIL simulation and off-line simulation are shown in Fig. 13.

Figs. 13 (a), (b), (c) and (d) were results obtained by the PHIL simulation and waveforms from top are matrix input voltage, input current measured on the three phase side, output voltage and output power of the MC measured on the single phase, respectively. Figs. 13 (e), (f), (g) and (h) were corresponding results which were obtained by the off-line simulation. The good agreement of the PHIL simulation and off-line simulation results indicates that the proposed modification of the PHIL simulation has no influence on the operation of the test MC.

IV. CONCLUSIONS

The power hardware-in-the-loop simulation of the GECS was described, in which the test target was the MC. This PHIL simulation had inductors in the simulation part and the real part and it was an inductor coupled system. This paper focused on the instability problem of the PHIL simulation. The following conclusions were made:

(i) Even the real system is stable; the PHIL simulation for it may lose stability due to the introduced time delay. Generally, a PHIL simulation having a larger time delay imposes more constrict requirements on the value of resistor *R*, inductor *L* and capacitor *C*, respectively, and as a result, it is easier to lose stability than the PHIL having shorter time delay.

(ii) For the inductor coupled PHIL simulation having very short time delay, such as the PHIL in this research, the value of the inductor is the most important factor that is responsible for the instability problem. To keep such type of PHIL simulation stable, simulated inductor (L_1) must be smaller than the real inductor (L_2). Moreover, larger value of the ratio of L_2 / L_1 means larger stable area.

TABLE VII
PARAMETERS USED IN THE OFF-LINE SIMULATION

Input filter	L_f= 4 mH,C_{in}=10 μF
Output filter	L_f= 4 mH,C_{in}=10 μF
Load resistor	18 Ω
Carrier frequency	10 kHz
Gain of the resonance suppression control	0.01
Output power of the MC	230 W
Output voltage of the MC	60 V

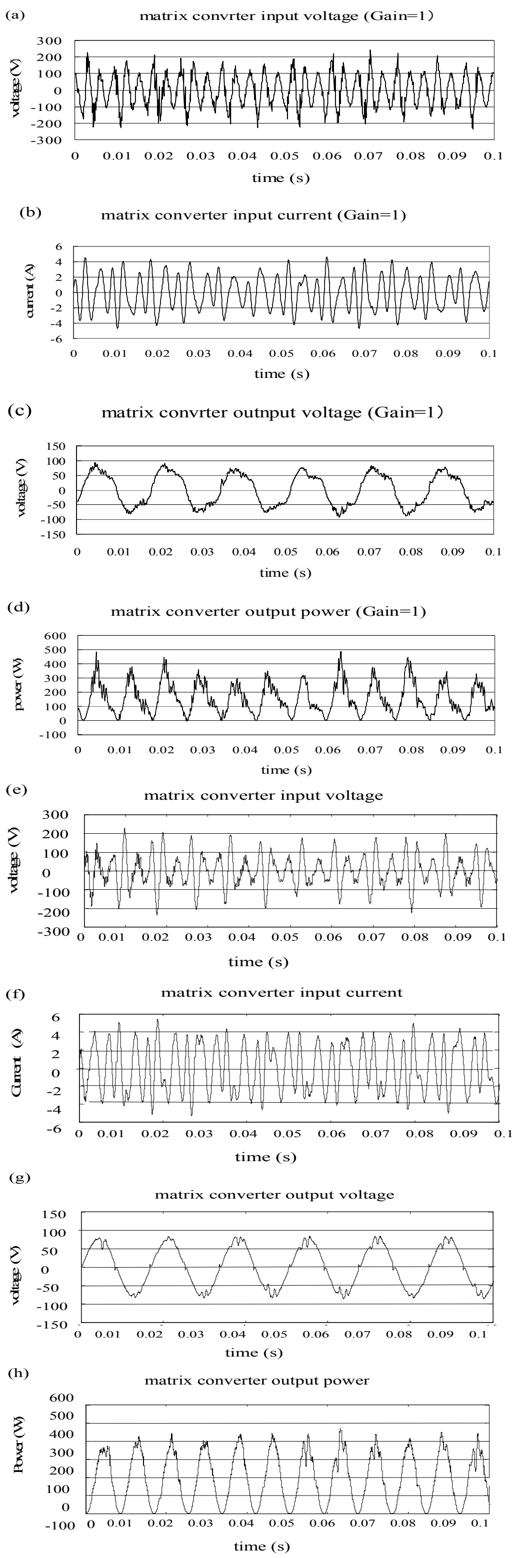

Fig. 13. Comparison of PHIL simulation results and off-line simulation results. (a), (b), (c) and (d): results obtained by modified PHIL simulation; (e), (f), (g) and (h): results obtained by off-line numerical simulation of the original GECS system without modification.

(iii) A method to solve the instability of the PHIL simulation was proposed. With the proposed method, the total of simulated and real inductors was kept constant while simulated inductor (L_1) and real inductor (L_2) were changed separately to meet the stability condition as that L_1 should be smaller than L_2. Analysis results showed that this method had no influence on the operation of the test MC and results obtained from off-line simulation of the original GECS system also verified the feasibility of the method.

The proposed solution can be a general approach for the mitigation of the instability of the PHIL simulation of the inductor coupled systems.

V. Acknowledgment

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